A Comparison between Volunteer, BioRID P3 and Hybrid III performance in Rear Impacts

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ABSTRACT

The most important tool to date for testing seat-systems in rear impacts is a crash test dummy. However, investigators have noted limitations of the most commonly used dummy, the Hybrid III. Although the BioRID I is a step closer to a biofidelic crash test dummy it is not user-friendly and the straightening of the thoracic spine kyphosis is smaller than that of humans.

The objective of this study is to compare the performance of the latest prototype of the BioRID, the P3, with those of volunteers. The BioRID P3 has new neck muscle substitutes, a softer thoracic spine and a softer rubber torso than does the BioRID I.

The BioRID P3 was validated against volunteer test data in both a rigid and a standard seat without head restraints. The dummy kinematic performance, pressure distribution between subject and seatback, spine curvature, neck loads and accelerations were compared to those of seven volunteers and a Hybrid III fitted with a standard neck. The BioRID P3 provided repeatable test results and its response was very similar to that of the average volunteer in rear impacts at $\Delta V = 9$ km/h.

AN ADEQUATE TOOL for performance testing of car-seat systems is required in order to reduce the risk for neck injuries in rear impacts. The current Hybrid III neck and torso are stiff and unlikely to interact with the seat back in the same compliant way as the human spine (Davidsson et al. 1998b, Geigl et al. 1995). A comparative study by Scott et al. (1993) showed that the head motion of a human was more complex than that of the Hybrid III in low speed rear impacts. The study also showed that the human subject's torso appeared to ramp up along the seat back while that of the Hybrid III did not.

Svensson and Lövsund (1992) and Thunnissen et al. (1996) developed and validated the RID-neck and the TRID-neck respectively for use with the Hybrid III. Although these necks have kinematic responses closer to those of humans, the Hybrid III torso seat interaction and loading to the base of the neck are not biofidelic. To attempt to eliminate these limitations, a Swedish consortium was formed to develop dummy prototypes with articulated spines and flexible torsos with human like surface contours. The first version, the Biofidelic Rear Impact Dummy (BioRID I), was found to be more biofidelic then the Hybrid III. It was also found to be repeatable and reproducible, but turned out not to be user-friendly (Davidsson et al. 1998b and 1999).

The aims of the present study are to validate the latest dummy prototype, the BioRID P3 (Davidsson et al. 1999), with volunteer test data and to compare its performance to that of a standard Hybrid III. The P3 prototype has a softer thoracic spine and softer torso than does the BioRID I. The neck muscle substitutes, the spine-torso interface and the arm attachments were also redesigned.

MATERIALS AND METHODS

The validation of the BioRID P3 (Davidsson et al. 1999) was done using data from a range of tests carried out on seven volunteers (described in detail by Ono et al. (1999a)).

DUMMY DESIGN – The BioRID P3 has a softer torso and thoracic spine than the BioRID I. The arm attachments, neck muscle substitutes and interfaces between the spine and torso have been re-designed. These changes were introduced in order to increase the upward motion of the T1 and to make the BioRID more user-friendly.

Torso - The BioRID P3 chest and abdomen, which are moulded as a single silicon rubber unit, is softer than that of the BioRID I. This, in conjunction with an adjustable spine and water filled cavity, facilitates forward out-of-position testing with a reasonable starting posture.

To reduce the relative angular displacement between the upper thoracic spine and the upper torso, two aluminium plates, which engage the two upper most spine-torso pins, were moulded into the rubber matrix (Figure 1).

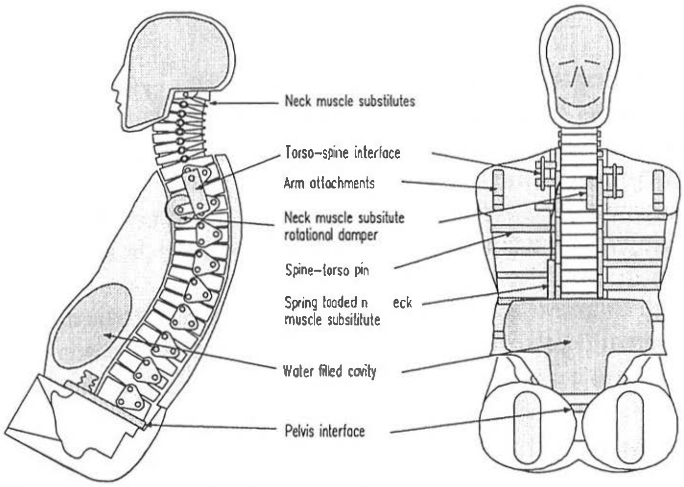

Figure 1: Schematic of the new BioRID P3 torso, arm attachments, spine, modified Hybrid III pelvis and head.

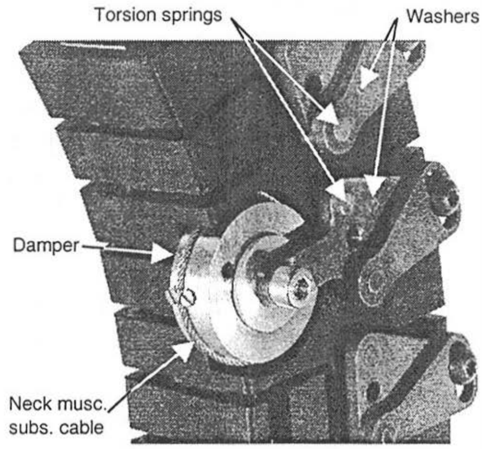

Figure 2: Photo of neck muscle substitute damper, thoracic vertebrae, torsion springs and washers.

Thoracic and lumbar spine - In the thoracic and lumbar spine, steel pin joints constitute linear torsion springs (Figure 2). In order to increase spine straightening in rear impact tests, the BioRID P3 thoracic spine pin diameter was smaller than that used in the BioRID I.

Cervical spine - To better replicate the human head retraction motion (head-lag) and thus more precisely predict injury risk, the neck was equipped with muscle substitutes. In this prototype, these substitutes consist of cables that originate from the head, in front and back of the occipital joint, and are then guided through C1 to T3 vertebrae. At T3 the cable loads are transferred to springs which are mounted in parallel with a rotational damper (Figure 1 and 2).

VALIDATION TESTS - The volunteer and dummy tests were carried out in 1998 at the Japan Automobile Research Institute (JARI).

Test set-up, volunteers and dummy configuration - A rigid wooden seat, with the same dimensions as an R16 seat, or a standard car seat was mounted to a trolley, to simulate a car-to-car rear impact the trolley collided into a damper (Figure 3). None of these seats were fitted with head restraints. Prior to the tests, the volunteers were placed in driver posture. They were asked to relax, to keep their heads at a level position and their palms supinated on top of a handle. The dummies were placed in a similar pre-impact position.

Seven healthy male volunteers (25±4 years of age), a BioRID P3 and a standard Hybrid III were subjected to a number of impacts. Four series of rear impact tests were included in this validation (R8R, R8S, R6RL and R6SL). The test conditions and anthropometric data are presented in Table 1 and the sled accelerations in Figure 4.

In order to mimic the pre-test spine curvature and pressure distributions between the seat and the volunteer backs, the BioRID P3 thoracic spine was somewhat straightened and the lower lumbar spine slightly flexed relative nominal values (BioRID P3). The initial BioRID P3 pelvis angle was 29 degrees. Two layers of elastic Lycra were placed between the seat and the undressed BioRID P3 in order to mimic the slack observed between the human skin and skeleton. The properties and positions of the polyurethane rubber blocks in the inter-spaces between the thoracic vertebrae determine the joint stiffness characteristics. The block size was varied in the tests (BioRID P3-A and P3-B, Table 1).

The Hybrid III was tested without torso flesh. To compensate for this, the seat back was covered with a 10 mm thick neoprene sheet.

Table 1: Test conditions for the volunteer and BioRID P3 tests (mean ± S.D.).

Series:	Test objects:	Sled ace. (m/s^2)	ΔV (km/h)	Seat type	Pre-test posture	Volunteers incl. in the test series	Age (years)	Height (m)	Weight (kg)
R8R	Volunteer (n=9)	36.2 (2.0)	9.3 (0.3)	Rigid	Driving	ABCDEFGBE	26 (4)	1.76 (.03)	71 (6)
	BioRID P3-B (n=1)	33.4	9.4	Rigid	Driving	-	-	-	77
	Hybrid III (n=1)	35.7	9.6	Rigid	Driving	-	-	-	77
R8S	Volunteer (n=9)	39.0 (1.7)	8.6 (0.2)	Standard	Driving	ABCDEFGBE	26 (4)	1.76 (.03)	71 (6)
	BioRID P3-A (n=1)	38.0	8.6	Standard	Driving	-	-	-	77
	Hybrid III (n=1)	36.8	9.0	Standard	Driving	-	-	-	77
R6RL	Volunteer (n=3)	26.4 (0.3)	7.4 (.02)	Rigid	Leaning	BCG	24 (1)	1.77 (.03)	71 (6)
	BioRID P3-A (n=1)	27.3	7.5	Rigid	Leaning	-	-	-	77
R6SL	Volunteer (n=3)	28.2 (0.7)	7.0 (0.0)	Standard	Leaning	BCG	24 (1)	1.77 (.03)	71 (6)
	BioRID P3-A (n=1)	28.7	7.0	Standard	Leaning	-	-	-	77
Repeat.	BioRID P3-A (n=3)	33.7 (.29)	9.5 (.03)	Rigid	Driving	-	-	-	77

ΔV — The presented ΔV is the mean and standard deviation of the maximum values in the test series.
Leaning — The volunteers and BioRID P3 were leaning forward 10 degrees from normal posture at the time of impact.
BioRID P3-A — Each of the thoracic joints was extended 1.3 degrees, L5-L4 and L4-L3 joints were flexed 3 degrees relative the BioRID P3.
BioRID P3-B — Each of the lower thoracic joints was extended 1.3 degrees, L5-L4 and L4-L3 joints were flexed 3 degrees relative to the BioRID P3. A 25 mm thick, 200*200 mm neoprene foam plate was inserted in-between pelvis and seatback to account for the flexibility in the human pelvis. The neck muscle substitute springs were pre-stressed 7 mm less than were those of the original BioRID P3. The size of the upper thoracic spine polyurethane rubber blocks was decreased to 3*15*15 mm.

Instrumentation - Film targets were fitted to the volunteers' heads at the auditory duct and to a rig that was fastened to the volunteer head by bite block and straps encircling the head (Figure 3). Three film targets were attached to the volunteers' upper torsos; two targets were mounted by means of lightweight holders to the skin covering the T1 process and sternum respectively, and one target was mounted to indicate the location of the T1 vertebrae centre. The iliac crest was located and fitted with a film target. Biaxial accelerometers (Ono et al. 1999b) were fastened to the head rig and skin covering the T1 processes. The locations of film targets and accelerometers were determined from x-ray images of the instrumented volunteers. The BioRID P3 was fitted with similar film targets and accelerometers. The T1 film targets and accelerometers were rigidly mounted to the T1 vertebra. The Hybrid III was tested uninstrumented.

A pressure sensor array (TEKSCAN, BIGMAT (Nitto) 2000 type, size 480×440 mm with 48×44 sensors) covered the seatback surfaces (Ono et al. 1999b).

Data acquisition - The accelerometer signals were filtered in accordance with SAE J211 and sampled at 8 kHz. All accelerometer signals were adjusted to zero offset before storage. An earth gravity-component was added to the sled accelerometer data prior to further processing. The seatback pressure was sampled at 100 Hz. The kinematics were recorded at 500 frames/s with a video (MEMORECAMNAC Inc.) and digitised in Image Express (NAC Inc.).

DATA ANALYSIS - Four coordinate systems were defined (Figure 3):

1. Sled coordinate system.
2. Head anatomical coordinate system: Its centre is located at the head C.G. Its x-axis is along the Frankfurt plane and is positive in the forward direction. Its z-axis is perpendicular to the x-axis and is positive in the upward direction. The coordinates rotate with the head.
3. T1 accelerometer coordinate system: Its z-axis is along the posterior surface of the upper thoracic spine and its x-axis is perpendicular to the z-axis. The coordinate system rotates with the posterior surface of the upper thoracic spine. Its centre is located close to the T1 processes/vertebrae

4. T1 anatomical coordinate system: Its z-axis is along the neck link, defined as between the T1 (estimated from T1 skin and sternum skin film target data) and occipital condyle (estimated from head film target data). The x-axis is perpendicular to the z-axis. In the volunteer tests, the centre is close to the T1 vertebra body and the coordinates rotate with the sternum skin - T1 skin film target plane. In the dummy tests, the centre is located at the neck base and the coordinates rotate with the T1/neck base.

Calculation of neck loads and head accelerations - Head rig acceleration data was used to calculate the head C.G. accelerations and upper neck loads (Ono and Kanno 1993). X-ray images of the instrumented volunteer head were used to locate individual head C.G. and occipital condyle relative to the film targets/accelerometers. The head C.G. location relative to the auditory duct was a result of a synthesis determined from relevant literature data (Ono et al. 1998) and the head mass properties were calculated from regression equations (Walker et al 1973).

Calculation of head-neck kinematics - Occipital condyle displacements were expressed with respect to a rotating T1 anatomical coordinate system. For the analysis of the head-neck kinematics, a two-link approach was used (Figure 3). The lower and upper pivot was located at the T1 and occipital condyle respectively. The neck link was defined between these two points. The volunteer T1 linear and angular displacements used in this validation were calculated as a weighted average value from the T1 skin and sternum skin film target data (Figure 3, Ono et al. 1999a). The weight factor was determined from x-ray images of the instrumented volunteer. The BioRID P3 T1 rotation was calculated from the T1 vertebra film targets. The change of distance between T1 and the iliac crest was calculated to give a single measurement of the straightening of the spine.

Calculation of seatback pressures - In the test with the rigid seat, the seat back pressure sensor surface was divided into six horizontal blocks of equal size (440*80 mm) and the average pressure between the subjects and the seatback was calculated for each block.

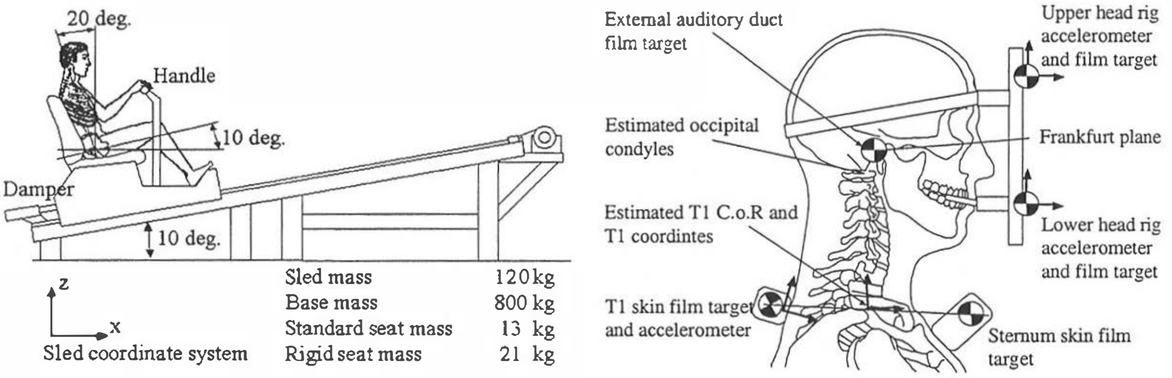

Figure 3: Schematic view of the sled, volunteer and R16 seat and of an instrumented volunteer head and T1.

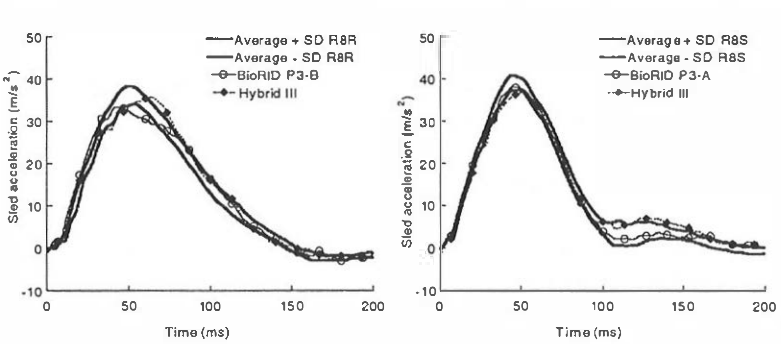

Figure 4: Sled accelerations for BioRID P3, Hybrid III and volunteers (mean±S.D., R8R n=9, R8S n=9).

REPEATABILITY TESTS - Three BioRID P3-A tests were carried out in a rigid seat at ΔV=9.5 (0.03) km/h. The repeatability of the BioRID P3 was evaluated by estimating the difference between test value and the particular average value, which was then divided by the average peak value.

RESULTS

This section presents the results from the validation of 1) the BioRID P3-B in a rigid seat, 2) the BioRID P3-A in a standard seat, 3) the BioRID P3-A in a forward leaning posture in a rigid and a standard seat. The repeatability tests results are also presented.

VALIDATION TESTS - For this validation, we have chosen to compare displacements, accelerations, neck loads and seat back pressures since these parameters are relevant indicators of dummy performance. The BioRID P3 responses compared with those of the volunteers are summarised in Table 2.

Table 2: A summary of the comparison of the BioRID P3 and volunteer responses.

Measure	Location	Direction	Rigid seat ΔV=9.3 km/h	Standard seat ΔV=8.6 km/h	Rigid seat, leaning ΔV=7.4 km/h	Standard seat, leaning ΔV=7.0 km/h
Linear displacement	Occipital cond. rel. T1	x	+	O	O	+
	T1	x	O	+	+	+
	Iliac crest	x	O	O	O	-
	Occipital cond. rel. T1	z	O	O	O	O
	T1	z	O	-	O	O
	Iliac crest	z	O	O	O	O
Angular displacement	Head rel. T1	Angular	O	O	O	O
	T1	Angular	+	O	+	+
	Neck link rel. T1	Angular	+	O		
	Head rel. neck link	Angular	O	O		
Acceleration	Head	Angular	O	+		
	T1	x	O	O		
	T1	z	+	-		
Load	Upper neck	My	To fast	+		
	Upper neck	Fx	O	O		
	Upper neck	Fz	O	O		
Change of distance	T1 to Iliac crest	-	O	O		

O Okay: The value was within the volunteer corridor (mean±SD) for the first 200 ms.
- The value was at some time during the first 200 ms less than the volunteer corridor (mean±SD).
+ The value was at some time during the first 200 ms larger than the volunteer corridor (mean±SD).

Rigid seat - The BioRID P3-B iliac crest x-displacement was within the volunteer response corridor during most of the impact time history, but the dummy motion was rather small in comparison to that of the average volunteer (Figure 5). No Hybrid III iliac crest x-displacement was observed.

When the T1 x-displacement were compared, the BioRID P3-B was within the volunteer corridor for the first 200 ms (Figure 5), but its peak value was 20 mm lower than that of the average volunteer. The BioRID P3-B T1 upward motion mimicked that of the average volunteer for the first 125 ms. Then the dummy T1 displaced downward while the average volunteer's T1 proceeded upward for another 50 ms (Figure 5). The BioRID P3-B T1 angular displacement was somewhat larger and occurred more rapidly than that of the average volunteer. The Hybrid III T1 displacements were very small.

The BioRID P3-B neck motion, i.e. occipital condyle relative T1 displacements and head relative T1 angular displacement, was similar to that of the average volunteer for the first 200 ms (Figure 5). The data reveals that the BioRID P3-B neck flexed and extended in a manner very similar to that of the average volunteer. Thereafter the BioRID P3-B occipital condyle started to move forward and upward relative to T1 while the volunteer displacements remained constant. The Hybrid III neck response was far too rapid.

The change in distance between the iliac crest and T1 (Figure 5) varied among the volunteers. The BioRID P3-B response resembled that of the average volunteer while the Hybrid III response was far from being human like.

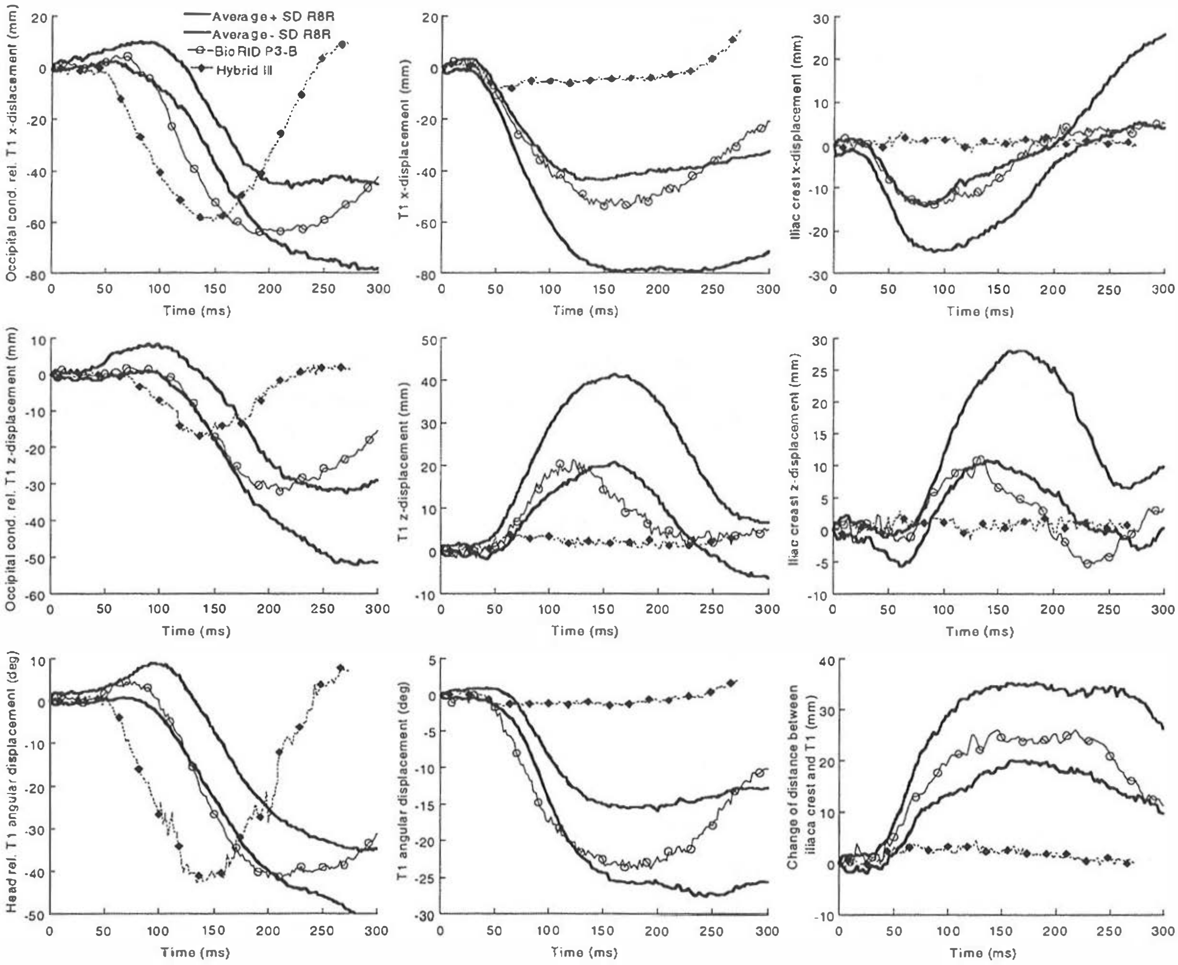

Figure 5: Rigid seat, ΔV=9.3 km/h, dummy displacements compared with volunteer corridors (mean±S.D., n=9).

The initial volunteer and BioRID P3-B lower neck flexion (neck link relative T1 angular displacement, Figure 6) were due to a rearward rotation of the T1. Neither the T1 rearward rotation nor the lower neck flexion were observed in the Hybrid III test. The BioRID P3-B lower neck extension started and reached its peak value earlier than did that of the average volunteer. The Hybrid III lower neck extension started to early and the peak value occurred too early and was too low.

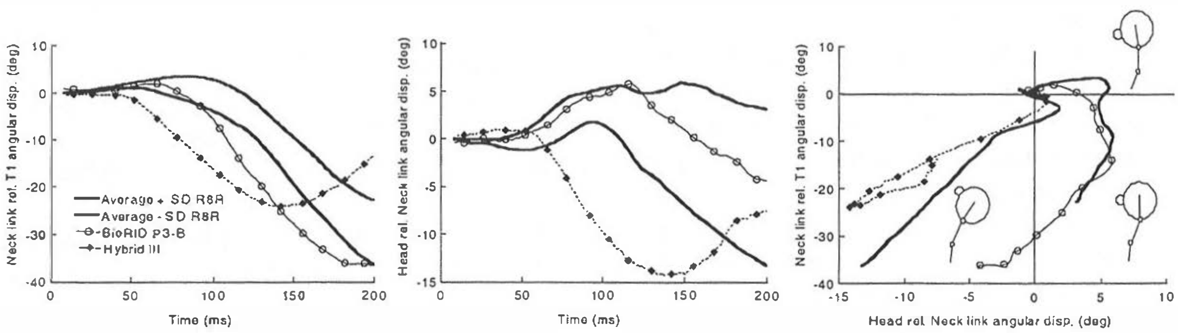

Figure 6: Rigid seat, ΔV=9.3 km/h, the BioRID P3-B and Hybrid III neck link data compared with volunteer corridors for the first 200 ms (mean±S.D., n=9).

When comparing the upper neck angle (head relative neck link angular displacement, Figure 6), the BioRID P3-B response was close to that of the average volunteer. The BioRID P3-B upper neck angle remained unchanged during the first 50 ms. The neck was slightly flexed until 150 ms and then extended. The Hybrid III response was far from that of the average volunteer. Its upper neck extended rapidly after 50 ms.

Figure 6 (upper versus lower neck angular displacement) shows that initially the volunteer upper and lower neck flexed, then the lower neck extended while the upper neck remained flexed, and finally also the upper neck extended. The second phase is often called s-shape or head retraction/lag. The BioRID P3-B neck response was within the volunteer corridor, but its head retraction was larger than the average volunteer response. Head lag was not observed in the Hybrid III test.

The head angular accelerations (Figure 7), neck shear and axial forces (Figure 8), and T1 linear accelerations (Figure 7) show that the BioRID P3-B resistance to flexion/extension in rear impact and as well as its mass properties were close to that of the average volunteer.

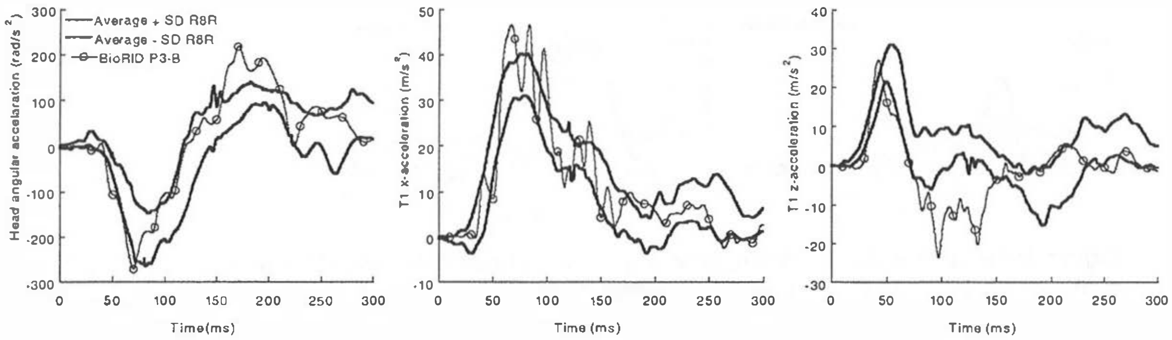

Figure 7: Rigid seat, ΔV=9.3 km/h, the BioRID P3-B head angular acceleration, T1 x- and z-acceleration compared with volunteer corridors (mean±S.D., n=9).

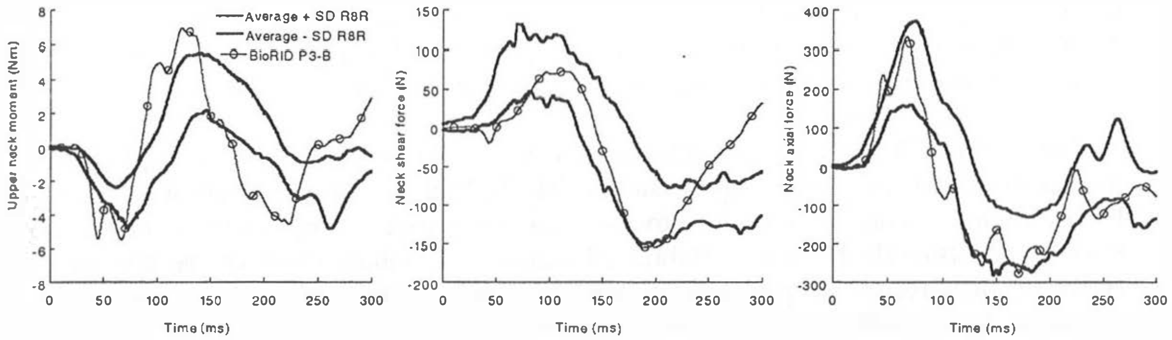

Figure 8: Rigid seat, ΔV=9.3 km/h, the BioRID P3-B upper neck loads compared with volunteer corridors (mean±S.D., n=9).

The BioRID P3-B seat-back pressure versus time resembled that of the average volunteer (Figure 9). The pre-impact block pressure distribution varied widely from one volunteer to another.

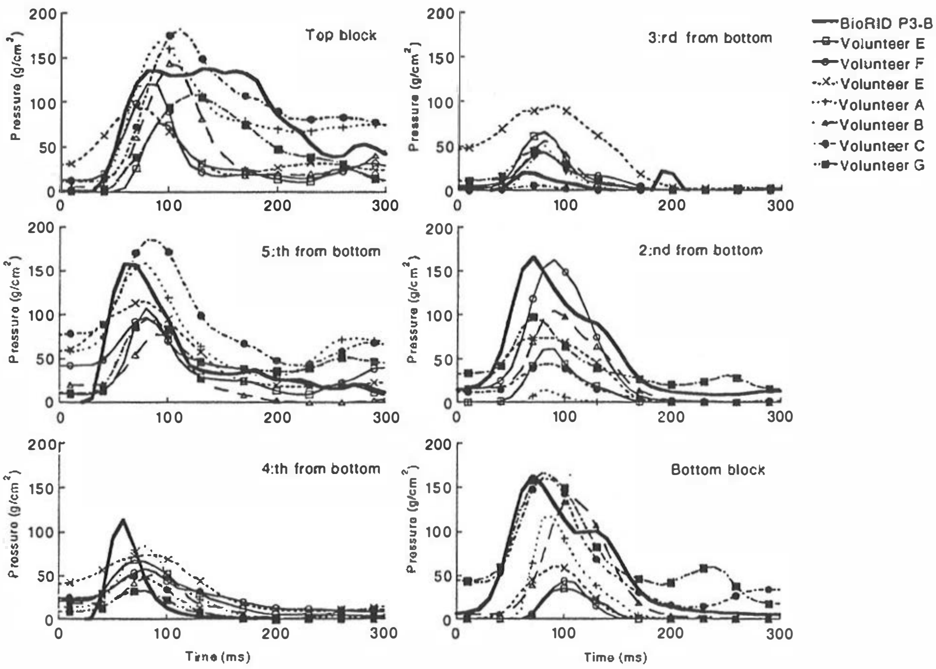

Figure 9: Rigid seat, ΔV=9.3 km/h, pressure between back of BioRID P3-B and six horizontal blocks of the seatback compared to that of seven representative volunteer tests.

Standard seat - The dummy iliac crest, T1 and occipital condyle (expressed in the rotating T1 frame) displacements are compared to volunteer data in Figure 10.

The initial dummy response depends on the load transferred between the seat and the lower torso of the dummy. The iliac crest motion into the seat is an indicator of the initial loading of the dummy. In these tests, the BioRID P3-A and Hybrid III iliac crest x- and z-displacements were similar to those of the average volunteer. The dummy peak values were, however, too low and durations were too short.

The BioRID P3-A T1 velocity into the seat was too high and the peak x-displacement was 20 mm larger than that of the average volunteer. The Hybrid T1 x-displacement was slighter than the lowest volunteer corridor boundary for most of the impact history. In terms of the T1 upward motions, the BioRID P3-A and Hybrid III motions resembled those of the average volunteer. However, their respective peak values were 15 mm and 25 mm less than those of the average volunteer. The BioRID P3-A T1 angular response occurred more rapidly than that of the average volunteer but was within the response corridor. The Hybrid III torso proved to be too stiff and produced a very small T1 angular displacement.

The BioRID P3-A neck response, that is the occipital condyle relative T1 displacement and head relative T1 angular displacement, was very similar to that of the average volunteer for the first 180 ms. The occipital condyle rearward velocity was, however, somewhat high between 120 and 180 ms. After 180 ms, the BioRID P3-A started the rebound phase while very little volunteer neck rebound was observed. The Hybrid III neck did not initially flex as did that of the average volunteer. The neck started to extend too early and the extension velocity was too large.

The change in distance between the iliac crest and T1 was similar for the BioRID P3-A and the average volunteer for the first 200 ms (Figure 10). It was close to zero for the Hybrid III test.

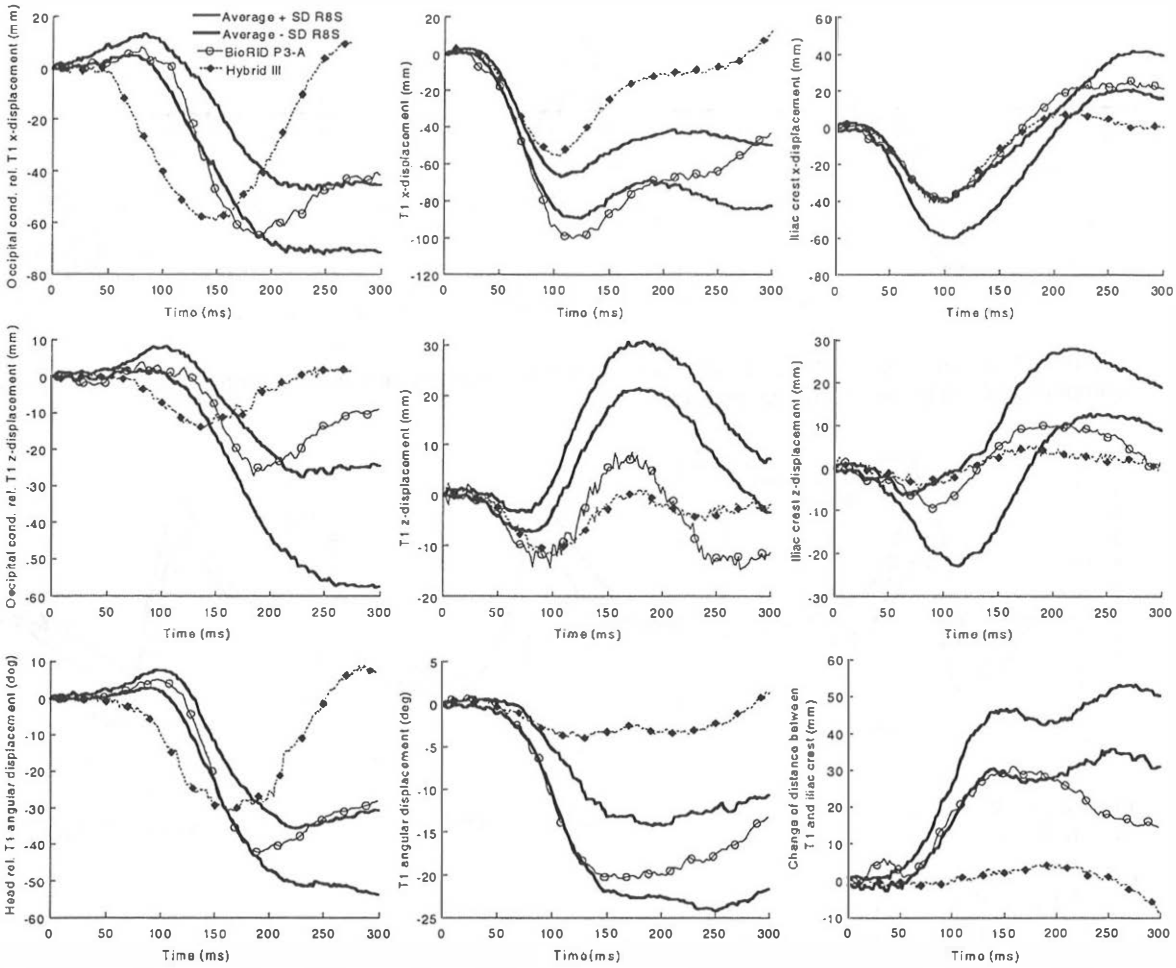

Figure 10: Standard seat, ΔV=8.6 km/h, dummy displacements compared with volunteer corridors (mean±S.D., n=9).

Dummy and average volunteer neck-link kinematics are presented in Figure 11. The BioRID P3-A and the average volunteer responded similarly for the first 100 ms. Thereafter, the BioRID P3-A head retraction was too large. This was mainly due to a larger/more rapid extension of the lower neck than desired. The Hybrid III neck kinematics was different from that of the average volunteer. Its lower and upper neck extension started too early, which resulted in no head retraction. The time of neck-link rebound started at 160 ms for the Hybrid III, at 200 ms for the BioRID P3-A and at 260 ms for the average volunteer.

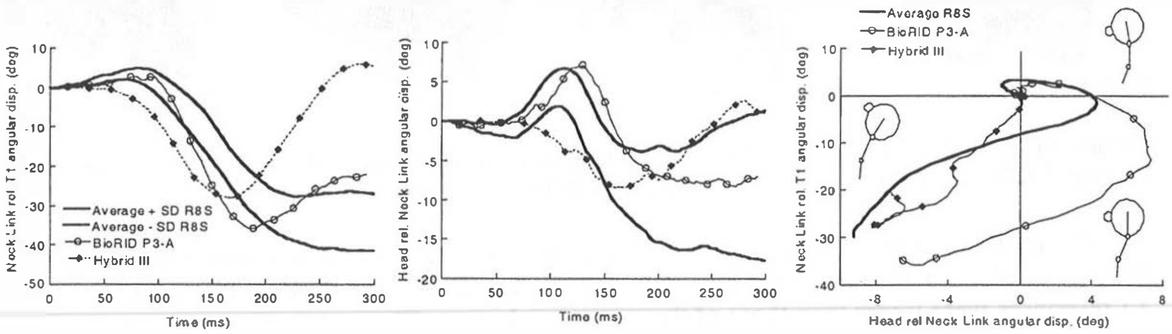

Figure 11: Standard seat, ΔV=8.6 km/h, dummy neck link angular displacements. Responses are compared with volunteer corridors (mean±S.D., n=9) for the first 300 ms or compared with mean value (n=9) for the first 200 ms.

The head angular accelerations (Figure 12), neck shear and axial forces (Figure 13), and T1 linear accelerations (Figure 12) of the BioRID P3-A were close to those of the average volunteer.

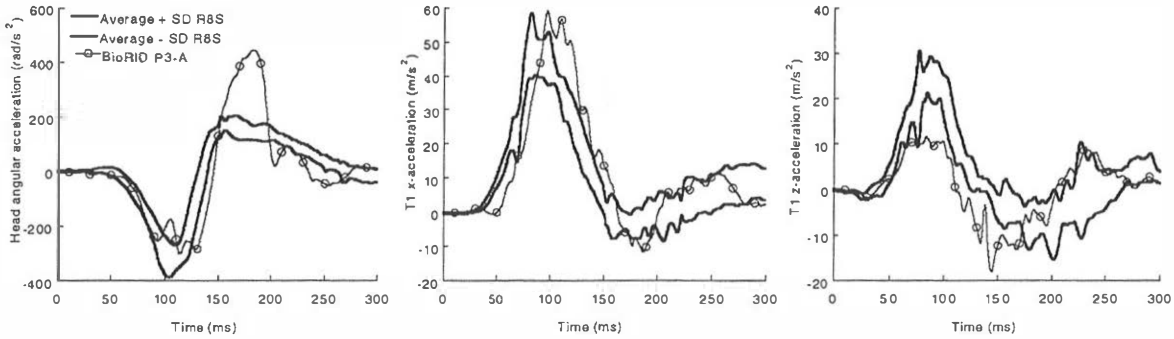

Figure 12: Standard seat, ΔV=8.6 km/h, the BioRID P3-A head angular acceleration, T1 x- and z-acceleration compared with volunteer corridors (mean±S.D., n=9).

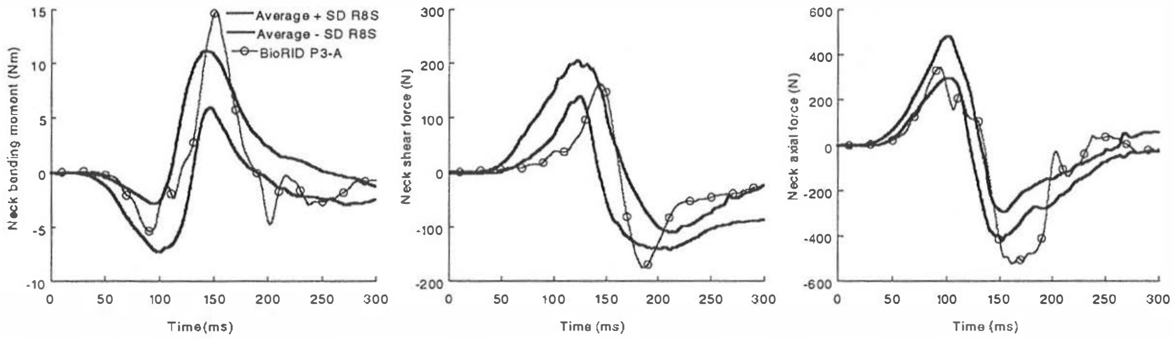

Figure 13: Standard seat, ΔV=8.6 km/h, the BioRID P3-A upper neck loads compared with volunteer corridors (mean±S.D., n=9).

The initial as well as the peak pressure distributions between the BioRID P3-A and the seat back were different from those of a representative volunteer (Figure 14). At maximum pressure, the seatback transferred loads to the volunteer's lumbar spine erector muscles, thoracic vertebra processes and medial part of the scapula bones. The pressure distribution varied between the volunteers. In the BioRID P3-A test, the seatback loaded the lateral part of the dummy torso and the pelvis back.

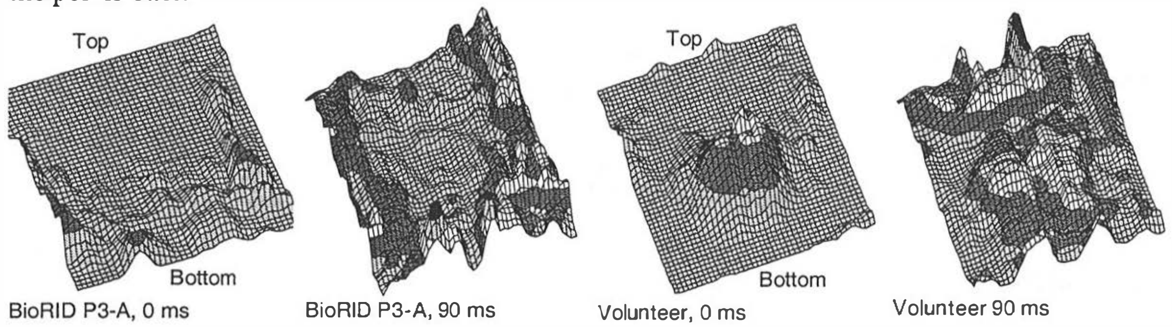

Figure 14: Standard seat, ΔV=8.6 km/h, pressure pattern at start and at the time for maximum pressure between BioRID P3-A back and seatback compared to those of a representative volunteer.

Leaning forward out-of-position tests - Subjects were asked to sit in a forward-leaning posture at the time of impact. This impact posture was reproduced with the BioRID P3-A. The BioRID P3 T1 responses were larger than those of the average volunteer (Figure 15). Its neck rearward angular response was, however, similar to that of the average volunteer.

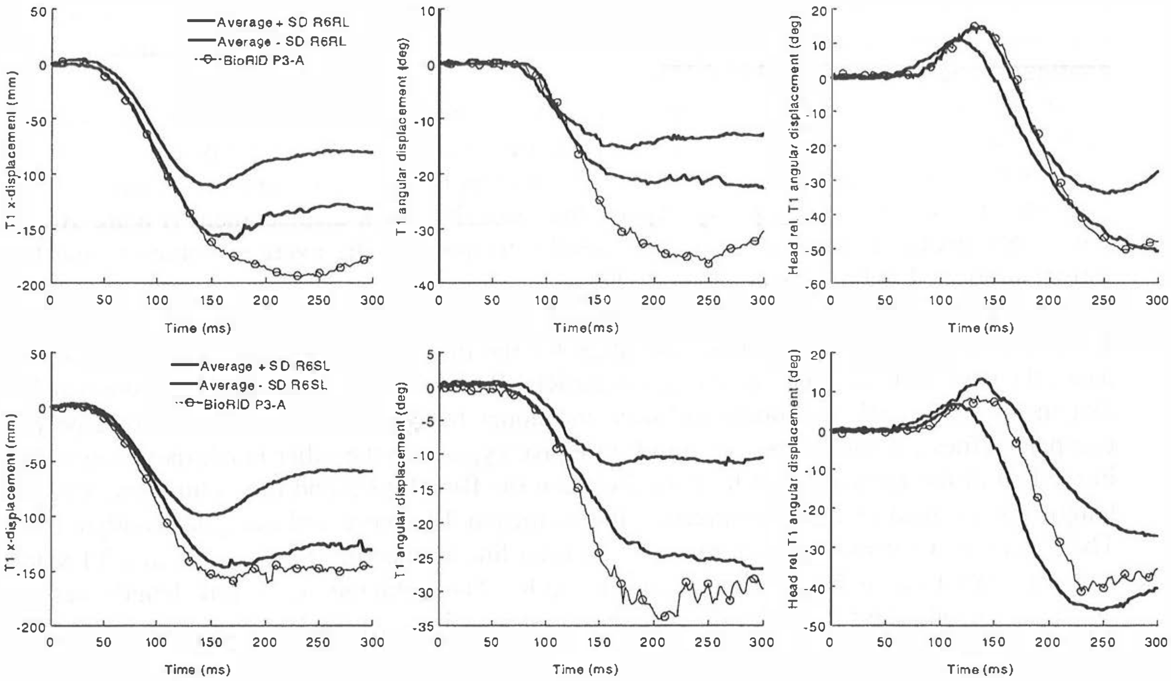

Figure 15: Leaning forward pre-test posture, rigid seat, ΔV=7.4 km/h (top) and standard seat, ΔV=7.0 km/h (bottom), dummy displacements compared to volunteer corridors (mean ± S.D., n=3).

REPEATABILITY – The repeatability of the BioRID P3 was taken as the difference between one test value and corresponding average value divided by the corresponding average peak value. The occipital condyle relative T1 and the T1 x-displacements were within ±10%, the head relative T1 and T1 angular displacements were within ±6%, and the head C.G., T1 and sled x-acceleration were all within ±4%.

DISCUSSION

DUMMY DESIGN – The reproducibility of the BioRID I was determined by Davidsson et al. (1998b). The design changes introduced in the BioRID P3 will most likely improve the reproducibility. For example, the friction in the BioRID P3 neck muscle substitutes have been reduced and its design has been simplified compared to the BioRID I.

Three identical BioRID P3 tests were carried out to highlight the repeatability of the dummy and test conditions. The data show that the dummy performs repeatable.

Two slightly different BioRID P3 pre-impact seating curvatures, A and B, have been used in this study in order to replicate the volunteers' spine curvature and seatback pressure. When the BioRID P3 spine pre-impact curvature was adjusted, its resistance to extension/flexion was affected. In other words, a straight BioRID P3 thoracic spine had a larger resistance to extension than did a thoracic spine in kyphosis posture. It is assumed that this effect resembles that of a human. There are, however, currently no reliable data available on range of motion or resistance to extension motion in the thoracic spine.

VALIDATION TEST - The volunteer surface EMG recordings (sternocleidomastoid, trapezius and paravertebral neck extensor muscles) indicated that most of the volunteers in this study were relaxed prior to impact (Ono et al. 1999a). The volunteers were, however, aware of the impending collisions and their kinematic responses were therefore probably smaller than those of a subject in an actual car-to-car rear impact. The dummy kinematics should represent those of the whole population of car occupants. Therefore, a dummy for rear impact testing should most likely yield a kinematic response that is somewhat larger than that of the average volunteer in this study. In addition, only young and healthy volunteers took part in these tests. They are probably capable of resisting relative body motions to a larger degree than older and less healthy subjects exposed to the same impact level. Therefor, the BioRID P3 torso and neck are slightly softer than are those of the average volunteer. The dummy head and T1 angular displacements and head lag (neck translation) were somewhat larger than were those of the average volunteer in all test configurations (Figure 5, 6,11 and 12).

The BioRID P3 T1 x-displacement was larger in the standard seat test than the volunteer corridor data (Figure 10). The seatback pressure reveals that the dummy upper torso was less supported, prior to impact, than was that of a volunteer (Figure 14). This slack between the dummy back and the seat back may partly explain the extensive T1 x-displacement (Figure 10). Dummy pre-impact seating posture must be very similar to those of the average volunteer and has to be further addressed in future validation studies.

The BioRID P3 occipital condyle relative T1 x-displacements in the standard and rigid seat tests were close to those of the average volunteer for the first 200 ms (Figure 5 and 10). On the other hand, the neck link data indicated that the BioRID P3 head lag was too large (Figure 6 and 11) and that the BioRID neck resistance to lower and upper bending, i.e. the intervertebral polyurethane bumper stiffness, could be increased in future prototypes. On the other hand, there was a difference in method of the estimation of head lag between the BioRID P3 and the volunteers. The neck link length was defined as a line connecting the estimated T1 centre and occipital condyle (Figure 3). The volunteer T1 centre was estimated to be on a line connecting the sternum and T1 skin targets and was thus located below the actual T1 C.o.R.. The volunteer neck link length was probably under-estimated, due to the chosen T1 displacement estimation method, and thus resulted in lower neck link angular displacements than actually occurred.

The Hybrid III torso was stiff and the T1 angular, T1 x- and iliac crest x-displacements were in all tests far from those of a human (Figure 5 and 10). The Hybrid III neck base was, therefore, accelerated forward more than was that of the human and the BioRID P3. The Hybrid III peak occipital relative T1 x-displacement was close to that of the average volunteer (Figure 5 and 10), but would most likely have been too low if the loading conditions at the base of the neck had been similar to those observed for humans. The Hybrid III occipital condyle relative the T1 frame x-displacements were due to the large extension of the neck and not due to humanlike head lag (Figure 6 and 11). The Hybrid III peak neck extension angle was close to that of the average volunteer. However, the head relative to T1 angle time histories were far from those of the average volunteer in both tests conditions (Figure 5 and 10).

For the BioRID I validation (Davidsson et al. 1998b), it was concluded that the T1 upward motion was too small. This lack of motion was mainly due to the insufficient change of distance between the H-point and T1 than desired. The length change was thought to be due to the straightening of the kyphosis of the thoracic spine. For these reasons, the BioRID P3 was fitted with a softer thoracic spine in order to allow for a larger T1 upward motion. In the tests with the rigid seat, this resulted in a BioRID P3 T1 upward motion (Figure 5) similar to that of the average volunteer. In the standard seat tests, the BioRID P3 change in distance between the iliac crest and the T1 was similar to that of the average volunteer. However, the BioRID P3 T1 upward motion was too small and that was thought to be due to excessive rearward rotation of the torso (which started after 100 ms) and due to less ramping up along the seatback than for the volunteers (which started after 160 ms).

It is important that the crash-test dummy be properly loaded by the seat structures in a rear impact seat-system performance evaluation test. In a preliminary test with the BioRID P3 placed in the rigid seat, it was observed that the pelvis (a Hybrid III pelvis fitted to the BioRID P3) was less compliant than were the average volunteers' pelvis (iliac crest x-displacement, Figure 5). In order to improve the compliance, a 25 mm thick padding was added to the back of the pelvis. A softer pelvis flesh or/and a reduced lumbar spine resistance to flexion is recommended for future BioRID prototypes.

Five observations were noted when comparing the BioRID P3 and volunteer seat-back block pressure in the rigid seat (Figure 9):

- The volunteer pre-impact seatback pressure was not used to control the pre-impact seating posture. As a result the pre-impact block pressure distribution varied widely from one volunteer to another.

- The BioRID P3 pre-impact seating posture was controlled carefully to produce a certain pressure distribution before impact. However, when the sled accelerates rearward prior to impact, the BioRID P3 rotates forward due to lack of muscle tone. This dummy rotation should be prevented in future validation tests since this rotation influences the dummy angular and rearward displacements and it was not observed in the volunteer tests.
- Throughout the impact, the dummy pelvis loaded the seatback somewhat more and the lower torso somewhat less than did most of the volunteers. This was most likely due to the 25 mm thick padding inserted between the pelvis and the seatback.
- The pressure on the three top seatback blocks indicated that the BioRID P3-B torso rolled up along the seatback, as did those five out of seven volunteers.
- The duration of the top block loading varied between the volunteers as it did between the dummy and volunteers. The BioRID P3 spine is probably too elastic and future spine prototypes should incorporate energy absorbents in order to reduce the rebound velocity and thus also the loads on the top seatback block.

The BioRID P3-A T1 displacements in a forward-leaning pre-impact posture were larger than those of the three volunteers (Figure 15). A number of explanations are possible:
- The dummy torso may have been slightly softer than that of the average volunteer.
- The volunteers might, in this part of the study, have been unusually tense during the time of impact.
- The volunteers managed to tense their muscles before the rearward motion ended and thereby restrained their torso and neck responses.
- The volunteers' backs may have been more flexed prior to impact and the pre-impact contact force between the volunteers' back and seatback differed from that between the back of the dummy and seatback. The volunteers could thus resist T1 displacements to a larger extent than could the BioRID P3.

The human skin can slide on top of the bone structures. In order to mimic this sliding in the BioRID P3 validation test, two layers of low friction fabric (Lycra) were placed between the dummy and the seat. The Hybrid III and BioRID P3 iliac crest z-displacements (Figure 5) suggested that seat evaluation tests with the BioRID P3 should be carried out with the dummy dressed in smooth clothing.

CONCLUSIONS

A dummy to be used in evaluation tests of seat-systems in rear impacts should predict the risk of injury to an occupant. Unfortunately, the relationship between dummy responses and the risk of sustaining a neck injury is not yet fully established. Until then, a dummy for seat-system evaluation in rear impacts should be as human-like as possible. The dummy should predict the loads, accelerations and displacements as close as possible to those experienced by humans in a rear impact. In this study, the BioRID P3 has been validated against volunteer tests at ΔV close to 9 km/h in normal driving posture and forward-leaning out-of-position posture in both a rigid and standard seat. The BioRID P3 response has been compared to the dummy currently used in rear impact seat system evaluations, the Hybrid III. For the first 200 ms after impact, the following findings were obtained:

1) BioRID P3 T1 rearward and angular displacements were close to those of the average volunteer while the Hybrid III displacements were far too small. The BioRID P3 T1 upward motion was smaller than that of the average volunteer, but much larger than that of the Hybrid III.
2) The BioRID P3 occipital condyle's forward displacement was close to that of the average volunteer, but the rearward displacement occurred more rapidly than did that of the average volunteer. The BioRID P3 occipital condyle's vertical motion was similar to that of the

average volunteer. The Hybrid III rearward and downward motions started too early and the durations were too short.

3) The BioRID P3 neck produced a limited flexion, then an s-shape motion and finally the entire neck extended. This was in accordance with the volunteer neck kinematics. The Hybrid III neck did not produce any s-shape motion.
4) The BioRID P3 head relative T1 angular displacement resembled that of the average volunteer. The rearward rotation occurred more quickly than did that of the average volunteer.
5) The difference in distance between the iliac crest and T1 was due to straightening of the thoracic spine kyphosis and was within the volunteer response corridors for the BioRID P3 while for the Hybrid III it was not.
6) The head and T1 accelerations and upper neck loads of the BioRID P3 resembled that of the average volunteer.

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